AN ASTROPHYSICS DATA PROGRAM INVESTIGATION OF HEAO/EXOSAT LOCATIONS AND IDENTIFICATIONS OF BRIGHT HARD X-RAY SOURCES

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Contents

Abstract ii

1 Introduction 1

1.1 Scientific Objective: Identification of X-ray Sources 1

1.2 Technical Context of the Investigation 1

1.3 Programmatic History 3

2 Scientific Results 4

2.1 Experimental Conclusions 4

2.2 Specific Astrophysical Results 6

3 References 10

ABSTRACT

The purpose of this research was to identify bright (greater than about 10^{-11} ergs cm^{-2} s^{-1}, 2–10 keV) hard X-ray sources discovered in the all-sky scanning surveys. The specific technique used here was the X-ray association of serendipitous sources found in pointed telescope missions with those in the NRL HEAO-1 catalog, using the A-3 modulation collimator positions to establish the connection. The results yielded objects which are scientifically important in their own right and helped build the A-3 catalog as a well defined, complete sample, analogous to the 3CR catalog in radio astronomy.

In addition we proved that the masked portion of the Einstein IPC fields included a significant content of serendipitious X-ray sources. We recommend that future X-ray telescope missions be required to preserved X-ray events from the entire field of view and to make these events available to the observer (at least as an option which the observer may choose).

1 Introduction

1.1 Scientific Objective: Identification of X-ray Sources

X-ray astronomy has played a role of selecting objects of great interest for astrophysical studies. Conversely, X-ray astronomy depends on traditional optical observations to acquire basic astrophysical parameters, such as the classification and distance, of a system. Thus, the optical identification of X-ray sources is both a motivation for doing X-ray astronomy and requirement for full exploitation of the information contained in the X-ray data.

Our goal has been to proceed toward complete identification of the NRL HEAO-1 catalog of bright, hard X-ray sources ($> 1.2 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the 2 to 10 keV band). This all-sky bright-source identification program is of great significance. These X-ray sources are the brightest because they are either the nearest or the intrinsically most luminous examples of their class. Either case is of great interest. We have recognized that as a set, these objects will be the most highly studied ones, and will form the cornerstone of future missions; for example, many of the ROSAT pointing targets have included these objects and ASCA and XTE will both largely study previously classified objects. Many will be the bright sources which are accessible to the AXAF dispersive spectrometers.

Our group had previously used the Scanning Modulation Collimator (MC) data from HEAO-1 to produce precise (few square arcmin for the weakest sources down to 0.4 square arcmin), multiple locations of the bright, hard X-ray sources found in sky surveys. We detected over 800 sources: Note that we could successfully use a detection threshold as low as 2.5 to 3 sigma (cf. Schwartz et al. 1985) since we only considered sources for which another experiment, the HEAO-1 Large Area Sky Survey (LASS), guaranteed existence to a higher level of statistical confidence. These sources represent an <u>all-sky survey</u> in the energy range 1–13 keV — the only such survey with good ($\sim 30''$) positional resolution. Although the detection threshold (~ 1.0 μJy at $\sim$3 keV) is significantly below that of the Uhuru and Ariel-V catalog limits, the detected sources are "bright" compared to the current sensitivity of X-ray telescopes. The survey thus selects impartially those X-ray sources in each class that are nearby or are intrinsically luminous.

The unique feature of the present project was the use of <u>unmasked</u> IPC fields. The work undertaken here was specifically oriented to using the MC data to determine what serendipitous sources detected by the Einstein telescope might be the correct counterparts of bright LASS sources. The present grant was strictly for efforts carried out on X-ray data at SAO; however, scientifically this work was done as a continuation of our collaboration as a single team with Drs. H. Bradt and R. Remillard of MIT, and Dr. I. Tuohy of the ANU/MSSSO, who performed optical observations using their own separate resources.

1.2 Technical Context of the Investigation

The HEAO-1 Large Area Sky Survey (LASS) experiment has produced the most comprehensive, all-sky catalog of X-ray sources in the 1 to 10 keV band. This sample is to a well-defined limit in <u>instrumental counting rate</u> corresponding roughly to 0.5 Uhuru Flux Units, which equals 1.2×10^{-11} ergs cm^{-2}s-1, 2 to 10 keV, or approximately 1μJy at 3 keV.

(The catalog lists some weaker sources, and the sensitivity varies over the sky as given in Figure 13 of Wood et al. 1984.) The majority of these sources were not identified by the LASS which greatly compromised the usefulness of this important survey to any systematic investigations. Identification of substantial numbers of sources from the A-1 catalog alone were not possible because of the large size of the actual location error boxes.

Another "problem" with the NRL survey is that conversion from instrument rates to physical flux units depends significantly on the X-ray spectrum, which is necessarily unknown for such weak sources. However, by identifying the source we can apply a statistical correction based on the mean conversion of LASS counting rate to flux, as measured for brighter members of the same class.

The importance of pursuing the complete identification of sources detected in the HEAO-1 "magnitude limited" survey of the whole sky can hardly be overstated. The revised 3rd Cambridge Catalogue of Radio Sources published by Bennett (1962) still gave the basis for the major review of radio identifications ten years later (Kristian and Minkowski 1975) and remained an important research topic for another decade (e.g., Smith et al. 1976; Spinrad et a. 1981; Spinrad and Djogovski 1984). The extragalactic X-ray survey work of Piccinotti et al. (1982) is greatly extended in the galactic plane and to fainter limits, by the LASS survey.

In pursuing identifications we recognized that the catalogued LASS positions are substantial underestimates of the 90% confidence location error box. This situation is not unusual for scanning, mechanical collimators and may be due to violations of fundamental data analysis assumptions such as that the source is constant in time, or that it is the only source in a region of constant sky background. Our experience shows that a confidence region of greater than 90% is obtained by extending the reported location along <u>either</u> its length or width in both directions by the reported dimension in that direction. With this fact understood, the LASS IS AN EXCELLENT AND IMPORTANT CATALOG. Of 842 sources listed by Wood et al. (1984) we considered 378 for this project (the remainder had either certain or suggested identifications). We found roughly 460 IPC pointings near fields of 197 out of these 378 unidentified sources.

We used Einstein observatory IPC data from all fields which overlap, in any part, our judgment of the true location allowed by the quoted LASS error box. We performed a unique analysis of the Einstein data. This was simply to produce the <u>unmasked</u> IPC image of each field, to look at it on the HEAO Image Processing (HIP) display system, and to add whatever subjectively appeared to be a source to the list of sources automatically detected in the masked IPC region. Our rationale was that the bright sources which may be LASS counterparts would still stand out in the higher background region around the IPC edge, which is masked off in normal processing, or would be noticeable "leaking" from under a rib. The fact that such X-ray sources would also be required to fall in an MC location, and would ultimately be tested by whether a viable optical counterpart existed, gave us little concern that some of these subjectively selected sources are spurious.

Use of the unmasked field gave essentially the full $1^\circ.25 \times 1^\circ.25$ field of view of the IPC, in contrast to the 0.6 sq. degrees used in the Medium Sensitivity Survey (cf. Gioia et al. 1990). One purpose of the Medium Survey was to measure accurate fluxes of each source, to be used for statistical investigations. This caused them to reject large areas of the IPC around the outer edges and ribs. Of course, they also rejected the target of each field and any fields which were deliberately pointed near previously known strong sources, or fields with extended sources. The Galactic Plane Survey (Hertz and Grindlay 1984) used similar selection criteria with about 0.8 sq. degrees per IPC field. Thus many LASS counterparts were overlooked in those surveys.

We find that sources which appear as weak as 10^{-12} ergs $cm^{-2}s^{-1}$ (0.2 to 3 keV) in the Einstein IPC (and perhaps even weaker when near a rib or field edge, or in the HRI) are nonetheless viable candidates for a LASS source. Variability, or low energy absorption in the source or in our galaxy, may account for these differences. At or above this flux level Gioia et al. (1984) report 0.18 sources/deg^2. We find the enlarged NRL error regions have areas of 0.5 to 5 deg^2, and thus a chance of 9 to 60% of containing an unassociated serendipitous source as bright as 10^{-12} ergs $cm^{-2}s^{-1}$. Our MC positions reduce the allowed location by a factor of 8 to 100 (typically 30), thus there is typically only a 0.6% chance (range 0.1% to 11%) of an unassociated Einstein source of this strength.

1.3 Programmatic History

This project was first proposed in response to the first Satellite Astrophysics Data Analysis Program (SADAP, later called Astrophysics Data Program, ADP) announcement, as a three year study. It was accepted for one year, starting October 1, 1987. We replanned that fiscal year to be an extended "pilot study" of about 60 sources to access the "end-to-end" efforts and yield. In December 1987 we responded to the second ADP NRA, proposing the final two years of our original program. This proposal was accepted for one year, which we devoted to extensive data aide labor to create the unmasked images, make hard copies of those containing new sources, and find approximate positions and fluxes of those sources. A proposal in December 1988 for the third year, to be devoted to intensive scientific analysis on results in the unmasked IPC images, was not approved. Instead, we continued examination of the IPC images on a no cost extension basis, and provided results directly to our collaborators, Drs. H. Bradt and R. Remillard of MIT and Dr. I. Tuohy of the ANU/MSSSO, for performing optical identification and publication.

Early in the first year of this program we realized that it would yield many (of order tens of) identifications and confirmations of X-ray sources. An initial group of identifications were presented at an AAS meting (Schwartz et al. 1988). However, since the unmasked IPC fields were not selected and examined in an unbiased and objective way, our team decided that these identifications should be published as part of "The HEAO-1 Modulation Collimator-LASS Catalog of Identified X-ray Sources," (Remillard et al. 1994), rather than as a "stand-alone" set of identifications. This catalog proved to be an extremely ambitious project. The present final report had been delayed deliberately, anticipating publication of the catalog, but is being issued now as the catalog nears its final draft version.

We conducted this investigation by first developing macros for the Einstein computer system for reconstructing and displaying unmasked IPC images (without redoing the aspect solution, source detection, output printing, etc.). A data aide ran these and produced hard copy output. The data aide examined this output for sources which were not catalogued in the automatic processing system. Rough positions were measured by pixel number on the HIP screen (since 1 to 3 arcmin accuracy was adequate) and they were added to the source list generated by automatic processing. The final step was to search for coincidences with the multiple, "diamond-shaped" modulation collimator positions. These were labor intensive tasks, and only about 1/3 of the X-ray sources were analyzed through the entire process.

2 Scientific Results

Examination of unmasked IPC images have led to identifications of HEAO-1 sources by a variety of means. Section 2.1 summaries the empirical results of looking at the IPC images, and Section 2.2 discusses specific astrophysical results.

2.1 Experimental Conclusions

Empirical conclusions may be summarized as follows:

1. Unmasked IPC images do reveal previously unrecognized, bright X-ray sources which are the counterpart of HEAO-1 survey sources.

2. Inspection of unmasked IPC images allows us to recognize IPC sources which are near ribs. Although these generally are detected by the automatic source finding algorithms, they appear too weak to be a HEAO-1 source unless susceptibility to shadowing by ribs is known.

3. Some IPC pointings at known astronomical objects have resulted in publications of the X-ray properties of the object <u>without</u> the realization that it is also the bright, hard X-ray source. Some of these may have preceded that NRL catalog publication (Wood et al. 1984), while others may not have realized that published NRL locations must be extended by at least one error box length or width to give a 90% confidence region. The existence of hard X-rays often extends or changes the detailed interpretation of the X-ray system.

4. Serendipitous IPC sources easily recognized in automatic processing as well as in the unmasked image, but which were in fields excluded by the Einstein survey projects, allow identification of HEAO-1 sources. For example, the Medium Sensitivity Survey (Maccacaro et al. 1982) is only for $|b| > 20°$ while the Galactic Plane Survey (Hertz and Grindlay 1984) is only for $|b| < 15°$. Both surveys exclude regions around previously known bright sources, as well as non-point source targets such as clusters of galaxies, supernovae remnants, and star associations.

5. The unmasked images reveal substantial numbers of previously unrecognized Einstein/IPC sources. These are genuine X-ray sources beyond doubt, but are definitely not HEAO-1 identifications. We believe such sources cannot be used as parts of any systematic "samples" or "surveys", because of their subjective selection and uncertain flux. Nonetheless we feel they should not be "lost", and that identifications should be pursued to find objects of special intrinsic interest, (see Table 1).

TABLE

SERENDIPITOUS EINSTEIN SOURCES
UNRECOGNIZED IN AUTOMATIC PROCESSING

IPC SEQUENCE NUMBER	TIME IN PROCESSED IMAGE (KSEC)	NEARBY HEAO-1 SOURCE	# OF NEW SOURCES
10150	5.2	H0448-041	6
5470	3.7	H0445-060	3
3748	6.3	H0437-088	0
7895	2.7	2H0447-037	3
3998	0.97	H0239-215	0
3445	0.3	none	1
2013/2014	7.1/5.4	H0239-215	0
2578	29.6	H0137-403	7
8384	2.0	H0345-452	1
227	0.6	H0128-139	2
329	1.3	4U0134-11	0
9113	2.1	4U0134&H0128	5
3843	2.1	H0419+280	2
4507	2.3	H0419+280	2
4514	2.8	H0419+280	1
3518	1.6	none	0
7374/5/6	2.8/2.1/2.0	none	0
3810	11.5	H0456+304	1
3841	1.9	H0456+304	0
2684	1.8	H0459+248	0
10153	4.7	H0409-078	0
865	3.8	H0409-078	0
521	4.2	none	2
3194	0.8	none	0
6706	1.4	H0422-086	1
3906/7	1.8/1.3	H0413-116	0
8422	1.5	none	1
4029	11.5	none	4
5782	1.5	H0419-577	1
1937/8	2.7/2.6	H0414-551	0
5726	0.8	H0414-551	0
7030	10.8	H0414-551	0

37 FIELDS

43 SOURCES

6. Unmasked images with no counterpart to the HEAO-1 source may substantially reduce the size of the HEAO-1 location uncertainty.

2.2 Specific Astrophysical Results

Among our astrophysical results, we discuss the following examples to illustrate the empirical conclusions of the previous section.

Figure 1 shows the unmasked IPC image of a field overlapping the source H0419-577. Note the heavy shading due to higher background along each edge and in the four corners. A previously unrecognized source is clearly seen inside the box marked "A". We roughly estimate its 0.2 to 3.5 keV flux as 5×10^{-12} ergs $cm^{-2}s^{-1}$, based on its ratio of counts to those of sources 1 and 2 which were detected by the automatic source fitting routines. Considering vignetting and conversion to the 2 to 10 keV band for a spectral index $\alpha = 0.7$ would increase this flux by a factor of 2 to 4. The position is on the extended NRL line of position, and inside the line of position from one modulation collimator (no detection in our other collimator, consistent for a source near our threshold sensitivity). There are about fifteen objects brighter than B=16 within several arcmin of the IPC location, but we know from two color Schmidt plates that none was strongly ultraviolet. The fifth brightest object is a quasar at z=0.104 whose spectrum is shown in Figure 2. This quasar is about fifteenth magnitude, and a certain identification for H0419-577 (category A of Remillard et al. 1986). Discussion of this object appears in Brissenden (1989), and Brissenden et al. (1994). We proposed ROSAT observations, based on the identification, and have reported preliminary results (Schwartz et al. 1992).

An Einstein pointing at the field of H0409-078 was excluded from the Medium Survey since it was deliberate target of a known bright X-ray source. The IPC detects the star SAO 130994 at 4×10^{-11} ergs $cm^{-2}s^{-1}$, and it falls inside an MC diamond. This is a known RS CVn object, number 76 in the list of Hall et al. (1986). The MC locations contradict identification of this X-ray source with 40 Eri (as tentatively listed in the NRL catalog, Wood et al. 1984), although Einstein does detect 40 Eri at 2×10^{-11} ergs $cm^{-2}s^{-1}$, .2 to 3.5 keV, but most likely as a stellar coronal source with $T< 10^7$ °K.

Similarly, the Medium Survey could not use an Einstein pointing at the previously known source H0448-041. The IPC detects the galaxy MCG-01-13-025 at a flux $\sim 4 \times 10^{-12}$ ergs $cm^{-2}s^{-1}$. It is near a rib, but probably not shadowed. Our MC locations confirm this as the identification of H0448-041, in this case verifying an identification suggested in the NRL catalog. Our optical observations show that this is a previously unrecognized, nearby AGN, We measure z=0.013, and a total magnitude V=14.2 for the galaxy.

We have found three objects studied by others as Einstein sources, for which the identification as a HEAO-1 source was previously unknown.

Einstein observations of RY Tau revealed the G star HDE 283572 as a very bright X-ray source (Walter and Kuhi 1981). Walter et al. 1987 discuss Einstein and EXOSAT observations of this object as a "naked" T Tauri star, i.e., a very young star but without significant circumstellar material. These authors' did not note the possible connection with the HEAO-1 source H0419+280. In our inspection of two unmasked IPC images of this region we found that the star is outside the NRL box, but clearly selected as the identification by

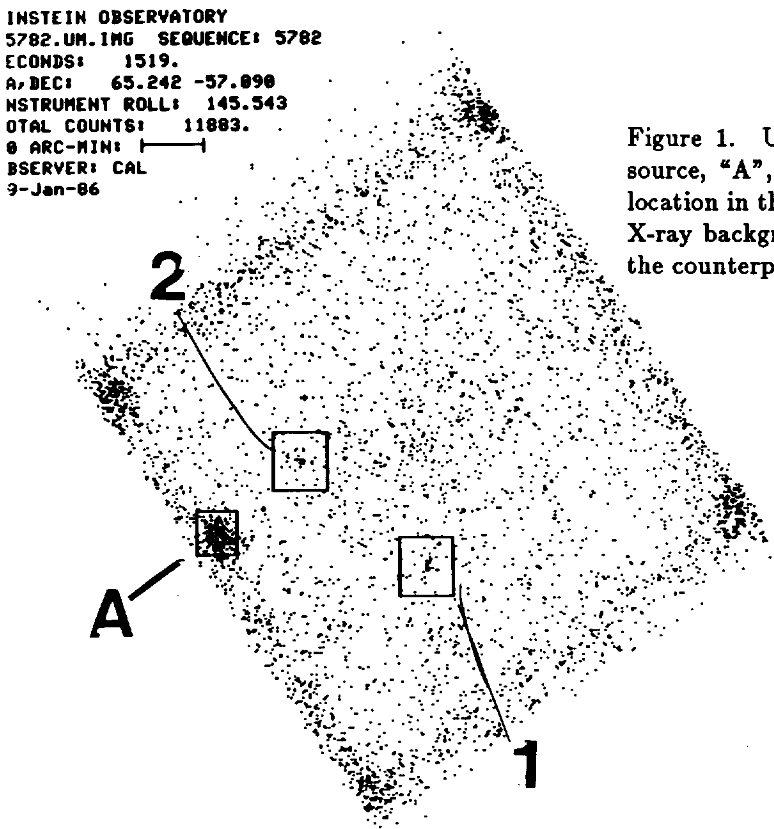
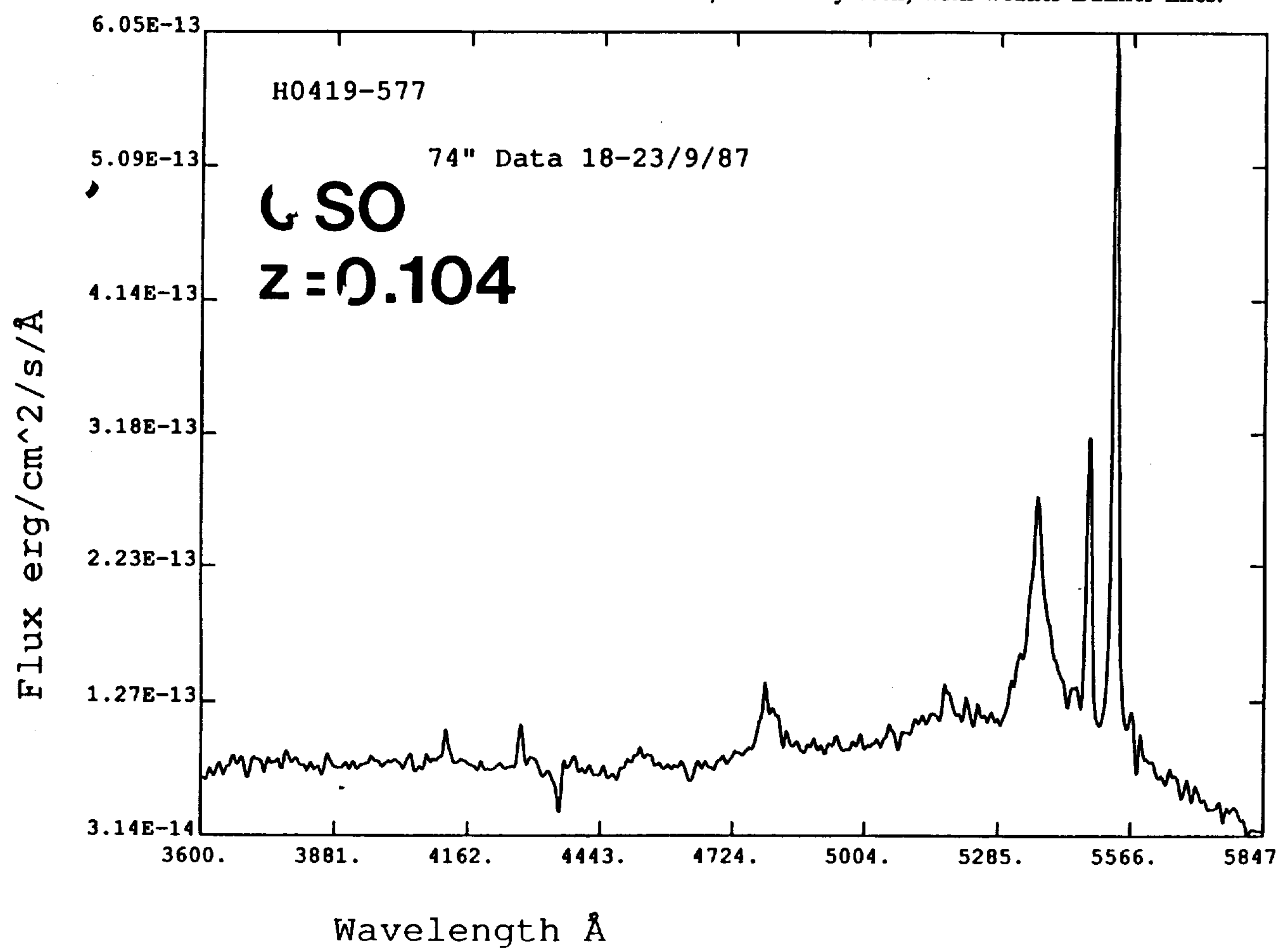


Figure 1. Unmasked IPC field showing a bright X-ray source, "A", which was previously undetected due to its location in the "masked" region of the IPC where the non-X-ray background is uneven and rapidly increasing. It is the counterpart to the NRL source H0419-577.

Figure 2. Spectrum of the optical counterpart of H0419-577. The object is a previously unknown quasar at z=0.104, with B=15th mag. Narrow [OIII] and broad Hβ, Hγ are clearly seen, with weaker Balmer lines.



our MC diamonds. This may have significant implications for the coronal models of this class of source. Although we cannot measure a spectrum directly, we see significant flux in the 3 to 10 keV range and therefore a hotter component than the 2 keV thermal model fit by Walter et al. This strengths the analogy to coronal emission from RS CVn stars, and complicates the detailed modelling since the hotter gas should have larger scale heights. Our look at the two unmasked IPC images allows a significant correction to the results of Walter et al. (1987): They report the flux in these two images, taken 3 hours apart, to be constant. However, we see that the second image is partially shadowed by a rib (Figure 3), and therefore really 1.5 to 3 times brighter. This argues against their conclusion of steady coronal emission and again strengthens the analogy (also predicted by Walter et al.) to RS CVn systems. We found another hard X-ray source, 1H0456+304, to be a T Tauri star discussed by Walter et al. (1988).

NGC 1566 was a previously known Seyfert observed as an X-ray source in a Columbia IPC project. Although just outside the published NRL location, the modulation collimator results indicate it as the HEAO-1 identification (to confidence level "B", cf. Remillard et al. 1986). Both MC and another unmasked IPC image deny the suggested identification of 4U0423-53 with the galaxy cluster SC0417-558. Instead, it is also the X-ray source H0414-551 = NGC 1566.

Einstein observations of the quasar PKS0405-12 by Padrelli et al. revealed a source of flux 5×10^{-12} ergs $cm^{-2}s^{-1}$ in the IPC. Due to the bandwidth difference, and in particular instellar absorption, this can easily be consistent with the flux 1.8×10^{-11} ergs $cm^{-2}s^{-1}$ 2 to 6 keV from H0413-116. Our MC locations clearly make this identification. The object is exciting because it is listed at V=14.6 in Veron-Cetty and Veron (1985) so that L_x/L_{opt} is not anomalously high, but $z = 0.574$ so that is is one of the most luminous ($L_x \sim 10^{46}$ergs/s) and brightest X-ray sources. It is known as an OVV quasar becoming as faint as V=17.1 (Hewitt and Burbidge 1980) so that future simultaneous X-ray/optical observations are important.

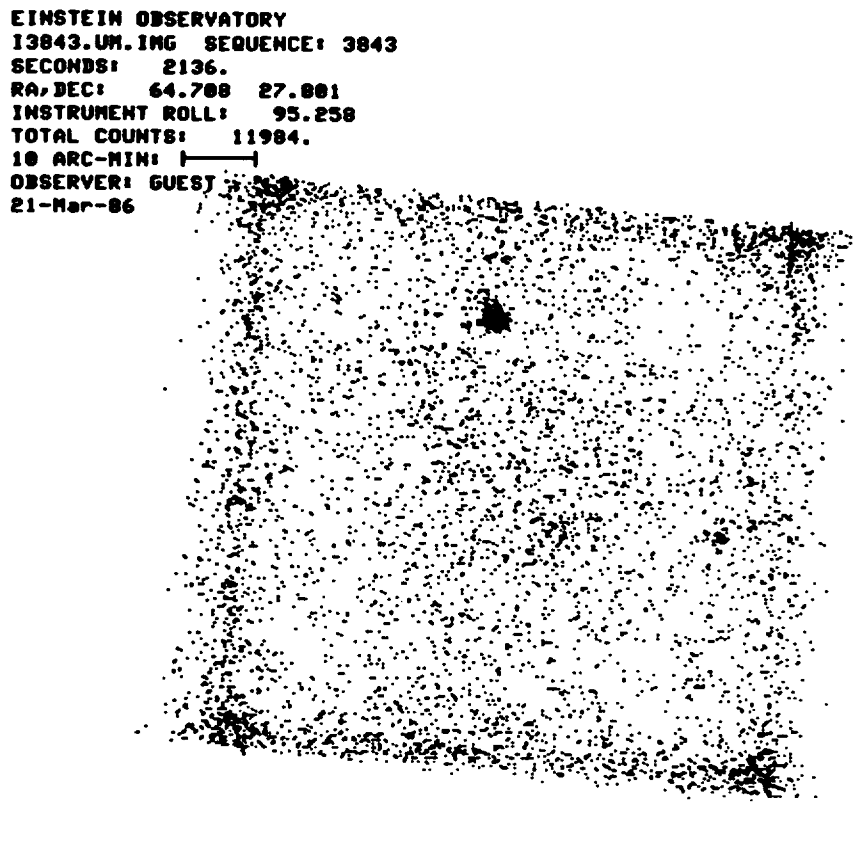


Figure 3: Unmasked IPC image of the second observation of HDE283572=H0419+280. In this observation the star is shadowed by a rib even though it appears brighter. Thus it has flared relative to an IPC observation 3 hours earlier.

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